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Multi-terminal VSC HVDC for the European supergrid: Obstacles

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ABSTRACT

For many, the supergrid is seen as the solution that allows the massive integration of renewable energy sources in the European power system. It connects different remote energy sources to the existing grid while offering additional control. It offers balancing through geographic spread and allows a more diversified energy portfolio. In the meanwhile it increases the security of supply.

However, technical limitations exist, and it is not yet possible to construct such a supergrid. Several outstanding issues need to be solved. This paper first describes the potential and need for a supergrid. The paper focuses on a meshed, multi-terminal VSC HVDC, and it is explained why this relatively new technology is believed to be the best suitable one for such a grid. The different difficulties or challenges that still exist are addressed. Not only the remaining technical limitations are addressed, but also the techno-economic, control and operational issues are discussed, as well as some regulatory obstacles.

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1. Introduction

For many, the supergrid is one of the solutions that allow the massive integration of renewable energy sources in the system [1]. Especially for Europe, where large amounts of renewable energy are available on remote locations, often offshore or near the sea. These renewable energy sources mostly have a variable and, to a certain degree, unpredictable generation output. Balancing them is seen as one of the main issues in the integration of renewable energy sources. The second issue is to transmit the power from remote locations to load centers. The long distance transmission of energy puts extra pressure on the already heavily loaded transmission system and because of the variability of the renewable energy sources, more transmission lines are needed for the same amount of energy delivered [2,3]. However, transmission system investments, especially new lines, have been limited in densely populated Europe, mainly because of opposition against overhead lines for environmental, health or political reasons. Furthermore, the transmission of large quantities of electric power underground (or undersea) is virtually impossible using AC because of the capacity of the cable systems.

A future supergrid or a new backbone transmission system has the potential to solve the aforementioned problems.

By connecting different energy sources such as wind, hydro and solar, the variability of the renewable energy sources can be reduced because of the limited correlation of different weather systems. Wind energy from the north of Europe can be partially balanced with wind from Spain or solar energy from the Sahara dessert. The remainder can be balanced by hydro energy, possibly from Scandinavia or the Alps. It could even allow the connection to the vast geothermal energy resources of Island. Many supergrid topologies have been proposed by different organizations [4,5] and also by environmental organizations [6], it is considered to be one of the most important options to reach a cleaner energy provision.

These projects and ideas have received widespread attention from both the politics and the press. However, within the technical community, skepticism in a large amount exists. The reason is that there is currently no technology that is ideally suited for such a supergrid and a number of developments are needed before a supergrid can actually be implemented.

This paper focuses on the European supergrid because of the strong strive for an environmental energy supply with low CO_2 emissions and the existing limitations in transmission expansion. However, most conclusions are also valid for other regions.

In the remainder of this article the current outstanding issues and limitations are discussed. In Section 2, the choice for multi-terminal VSC HVDC is explained and the technical state and its limitations are discussed. In Section 3, the outstanding control issues are covered. The operational and techno-economic sides of the supergrid are covered in Sections 4 and 5. In Section 6, the road towards the supergrid is explained. Section 7 concludes this article.

2. Technical

2.1. Transmission technology

A new backbone transmission system can be built using traditional alternating current (AC) or direct current (DC) technology. AC systems are well-known technologies, offering a cheap and reliable solution for high power transmission using classic overhead lines. DC systems on the other hand experience much less problems with long distance power transmission, especially when cables are used. As such, a DC overlay grid seems to be the most appropriate solution when cables are needed.

2.2. HVDC technology

HVDC has been in use for well over 50 years. Applications of HVDC are

- bulk transmission of energy over long distances;
- interconnection of asynchronous systems (possibly back-to-back);
- undersea connections.

The most common and oldest technology is based on current source converter (CSC), also called line-commutated converter (LCC). It uses thyristors as switches and it has a constant DC current. The DC voltage is controlled to alter the power flow.

Voltage source converter (VSC) HVDC has been developed in the mid-90s and since then a number of applications have been built. VSC HVDC uses IGBTs and as such it is able to independently create an independent AC voltage waveform. This allows the connection to weak islanded grids and offers black-start capability. An example is the connection to offshore wind farms, which is virtually impossible when using LCC HVDC. The VSC converter delivers a constant DC voltage and the current is controlled to alter the power flow. This allows the use of the easier and cheaper XLPE cables instead of mass-impregnated oil-filled cables. Fig. 1 shows the online schematics of the two technologies.

Currently there are two main VSC HVDC technologies which use a different concept to achieve a similar result. One concept uses a 2- or 3-level converter to deliver a PWM signal [7], while the other concept uses a multilevel modular converter [8]. Although they are fundamentally different converter technologies, the operation in the power system is similar.

The losses in DC lines are lower compared to those in AC systems, but the converters exhibit significant losses. The current state-of-the-art LCC HVDC converter has 0.7–0.8% losses at full

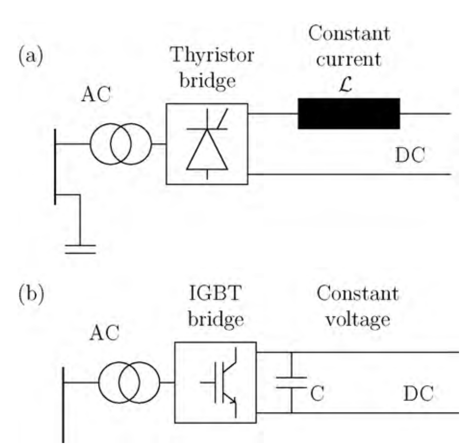

Fig. 1. CSC/LCC and VSC HVDC one line diagrams. (a) Current source converter. (b) Voltage source converter.

load, while the existing VSC HVDC links have 1.7% losses per converter. The losses of the VSC converters are significantly higher because of the switching frequency (1–2 kHz). New VSC systems with losses as low as 1% per converter are expected [9].

2.3. VSC HVDC for MT

VSC HVDC is the most appropriate technology for multi-terminal applications as it uses a common DC voltage, making parallel connections easy to build and control. LCC HVDC is much more troublesome to control in a parallel multi-terminal configuration, and especially changing the power direction in a single converter without interruption is problematic. Operating a multi-terminal LCC HVDC system with many terminals with constantly changing power flows might result in an unreliable system. The possibility to connect islanded grids to a VSC HVDC converter is another important advantage.

At this moment, only LCC HVDC has been used for MT HVDC applications. Most notable are the lines from Hydro-Quebec to New England and the connection between Italy, Corsica and Sardinia. Both have three terminals (although the first actually has five terminals, only three are in operation). At the time of their construction, VSC HVDC was not yet developed. A new multi-terminal connection is planned in Sweden (with a connection to Norway), where VSC HVDC will be used. Also this connection will have three terminals.

2.4. Why not AC?

The use of AC is disregarded as a potential option for a future supergrid in Europe. However, AC systems are capable of carrying large quantities of electric power over large distances when ultra high voltage (UHV, 1000 kV AC or higher) is used. AC systems using UHV voltages have been developed already in the 1970s, and are planned and installed in China. The technical reasons why UHV AC is not seen as a potential technology for the supergrid are:

- DC line losses are lower (no skin effect, no proximity effect);
- AC cable solutions for the needed high voltages are not yet available;
- AC cables experience a high charging current which limits their length. Long AC cables at very high voltages are difficult to construct and expensive;
- offshore resources, as well as connections outside the main continent, are virtually inaccessible when using AC;
- HVDC offers an inherent active power control, making it more flexible in use and easier to limit overloads in the system.

There are also non-technical reasons which are in favor of DC over AC technology. Using cables that cause no visual pollution and emit no varying electromagnetic fields, much less opposition and problems with licensing and construction are expected. Overhead lines are very difficult to construct because of non-technical issues. Furthermore, using sea cables allow a fast and relatively cheap cabling because few joints are needed [10].

Fig. 2 shows a graphic representation of the relative costs of HVDC and HVAC systems. The differences in cost price for an installation in countries such as China and India is predominantly influenced by the easier permitting process and the lower amount of "special" considerations to be taken into account such as deviations from the ideal path and sound protection.

In short, AC overhead lines might be an option, but building them is an issue because of political and environmental concerns and AC cables are not suited for long distance bulk power transfer.

However, UHV AC remains a valid option to serve as a supergrid in case these disadvantages are deemed less important. In regions with relatively seen more open space to place the transmission lines and where less offshore connections are needed, it can form the most techno-economic solution. Both northern America and China might benefit more from an AC supergrid than from a DC supergrid. Even in continental Europe this would be possible if the opposition against new lines would cease. Offshore and other remote resources would still require cable connections which makes AC no longer possible. A mixed AC and DC supergrid can be an option in that case.

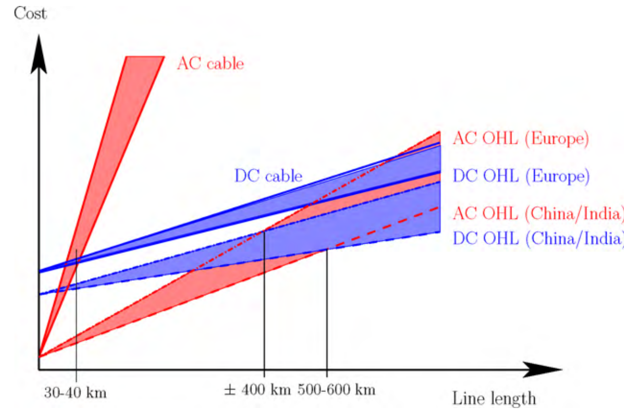

Fig. 2. Cost break-down for AC and DC systems.

The remainder of this paper focuses on VSC HVDC for multi-terminal systems.

2.5. Ratings

Considering the supergrid as the future backbone, it needs to offer high power transmission capabilities. Such a system should have higher, or at least similar, power transfer capabilities compared to the current 400 kV AC system. Depending on the configuration, a single circuit AC system can carry as much as 2700 A, or about 1.9 GV A at 400 kV, but higher is also possible. AC cable systems can support roughly the same power transfer, although over limited lengths [11].

In Fig. 3, the current ratings for HVDC systems are given, both LCC and VSC systems as well as overhead lines such as XLPE and MI cable types are depicted. Overhead lines for LCC HVDC are commonly used, but for VSC HVDC systems only one such system exists: the Caprivi link between Zambia and Namibia [7]. The figure shows that the voltage limit for cables is the limiting factor for the development of VSC HVDC of high power ratings. Higher voltage ratings (up to 500 kV) for DC XLPE cables are under development [14]. The numbers provided are indicative as they are subject to the installation and the environmental conditions.

Specifically for cables, the ratings are dependent on a number of factors such as the burial (direct burial, sea burial, tunnel, etc.) and the material used (copper or aluminum). Oil filled cables are not suited for long distance transmission as they require regular oil refilling.

2.6. What is a DC (super) grid

The definition of what a DC grid exactly is, it not trivial. When looking at possible MT HVDC configurations, different topologies are possible (Fig. 4) and it is not clear what the minimum requirements are to talk about a DC grid.

A First potential topology (Fig. 4a) is a simple multi-terminal system, which can be described as a DC bus with several tappings. While DC bus being the simplest form of a multi-terminal HVDC system, there are no meshes and no redundancy in the DC system itself. It is not really a "grid" as it offers no redundancy.

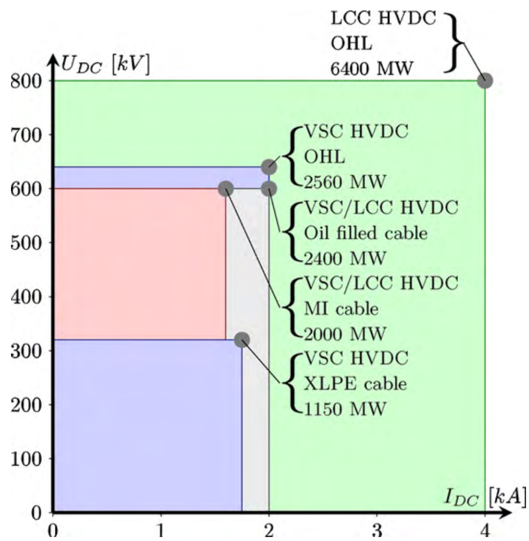

Fig. 3. Current possible (available or announced) ratings for HVDC systems (U_{DC} refers here to the pole voltage, in a bipolar setup, $P = 2U_{DC}I_{DC}$) [11–13].

Such a topology would typically be useful as an alternative to a single AC line, as a connection between two asynchronous zones with an additional connection, e.g. for an offshore wind farm.

A second possible configuration (Fig. 4b) is to have a grid of DC lines, where all the busses are AC busses, and the classic transmission line is replaced by a DC circuit with two converter stations. In this topology, all DC lines are fully controllable. It can consist of a mixture of LCC and VSC HVDC lines, and different lines can operate at different voltages. It is also easier to incorporate existing HVDC lines in the new DC grid. However, it needs a more complex control of the flows to keep the main frequency in case of different isolated AC grids or nodes. The protection in this topology can also be done using existing AC protection systems and equipment.

The third topology (Fig. 4c) proposes a meshed DC system, with a number of connections between the AC and DC system. Connections within the DC system without converter are possible, and there is redundancy in the DC system.

A major issue with the second topology is the amount of converter stations that are needed. When considering "normal" large grids, a rule of thumb says that the number of branches is usually 1.5 times the number of nodes. This would require $2 \times 1.5 \times \#DC_{nodes}$ converters. A grid using the DC topology as shown in Fig. 4c requires only $\#DC_{nodes}$ converters. This is especially important because converters are the most expensive, sensitive and lossy components of the DC grid. Only Fig. 4c is a "real" DC grid. If redundancy is needed in the supergrid itself, rather than it forming an alternative path to the AC grid, this is the only viable option. The first option can be seen as the first step towards a grid.

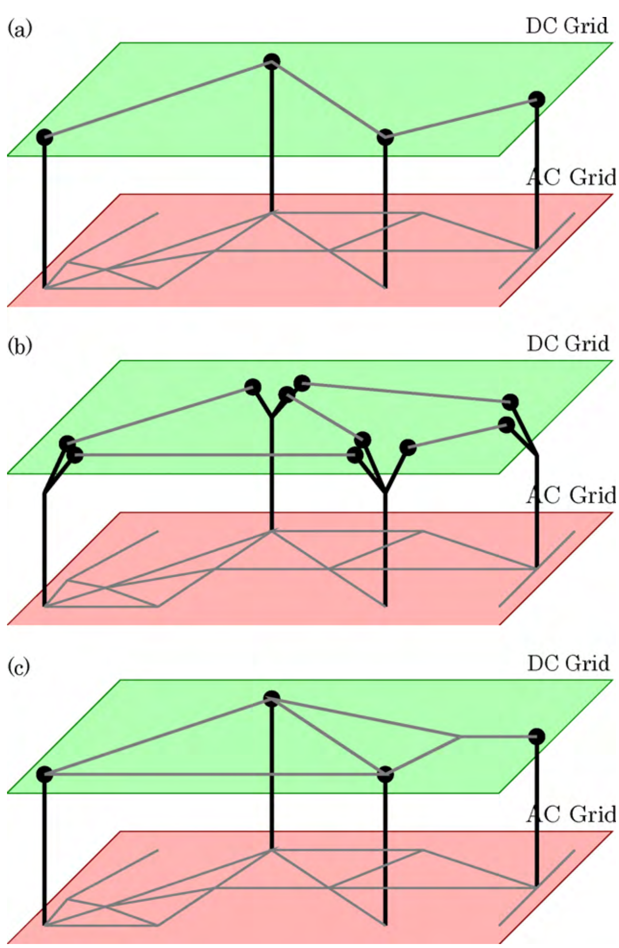

Fig. 4. Different potential topologies for DC grids. A converter is depicted as ●. (a) Multi-terminal with tappings. (b) Grid of independent DC lines. (c) DC grid.

2.7. Supergrid standards and interoperability

As with AC system, the DC grid requires a number of standards. One of the most obvious ones being the voltage level used. Once a level is chosen, it sets the voltage for the entire system. As with the AC system, several levels might be possible, but converting from one to the other is significantly more difficult. If the supergrid would be built as a connection of pre-existing DC lines, all of these must have the same voltage.

At this moment, there is no real standard for DC voltages. A voltage around 600 kV seems reasonable as it allows an easy connection to the existing 400 kV system, but higher voltage might be needed to accommodate the large flows.

If a supergrid would be developed, the equipment should be compatible between different manufacturers and DC technologies to ensure that sufficient alternatives are available and that competition between manufacturers exists. Vender lock-in is not acceptable in an international power system. Although different manufacturers might develop different VSC HVDC converter stations using different technologies and control algorithms, they are connected to the same system and they should work in the same system. The independent control functions should not interfere with each others. If the ramping speeds on the different converters differ significantly, unwanted dynamic effects might hamper the operation of the system. In case no single governing control exists, the different independent controls must be subjected to certain standards. The systems should also be compatible in terms of overvoltages (both emitted and immunity), protection systems, harmonics, communication protocols and other requirements.

The International Electrotechnical Commission (IEC) is currently working on a standard for HVDC technologies through its technical committee 115: "HVDC transmission for DC voltages above 100 kV".

Multi-terminal VSC HVDC systems are one of the subtasks of this technical committee, but unfortunately, no immediate action is planned in the line of standardization for a meshed HVDC supergrid [15].

2.8. Connection to the AC system

A supergrid would be used to transmit bulk energy. How much this "bulk" amount is going to be is yet unsure (see also Section

5.1), but connections with a rated power of several gigawatt are not unrealistic.

At this moment, there are only a limited number of connection points in the transmission system that can evacuate (or collect) such amounts of power. The existing system needs significant reinforcements to facilitate a supergrid. Furthermore, as most ideas indicate that a supergrid will be placed in the sea, the complete grid infrastructure needs to be re-oriented. At this moment the system is built from the generator locations (often thermal power plants or big hydro plants) to the load centers which are in big cities and highly industrialized areas. With the power coming from an offshore supergrid, the entire internal grid infrastructure will change.

Also the power flows throughout the system will change dramatically. The controllable power injections will make the AC power flows controllable up to a certain degree. This is addressed in greater detail in the next section.

Compared to the existing (400 kV) overlay systems, there will be fewer connections to the underlying systems. The existing AC to AC connections are made by "cheap" transformers while the DC connections require more complicated and expensive converter stations. As there will be fewer connections, each connection will have a large influence on the security of the system when taking $N-1$ security into account.

2.9. Protection and grounding

The protection system may be the main problem when considering HVDC technology for the next generation power system backbone. The existing VSC HVDC protection systems disconnect the entire DC system by activating AC switchgear (see Fig. 5). When a single line is considered, the difference between opening the faulted cable and removing the entire DC line is small from a system point of view. However, it is not acceptable to disconnect the entire DC backbone each time a fault occurs.

There are four main reasons why protecting a DC system is more difficult than protecting AC systems:

1. When a fault occurs in the DC system between pole and ground (shield), the capacity between shield and conductor will cause a discharge wave of amplitude $U = Z_0$ (with $Z_0 = \sqrt{L/C}$). This wave will propagate through the cable in both directions, slightly attenuated by the low cable resistance. Reflections will appear at intersections and other changes in characteristic impedance. The characteristic impedance of an XLPE cable is typically well below 100 Ω, and significantly lower than that of overhead lines. This leads to very high short-circuit currents, with steep wavefront. In a typical cable system, the traveling wave time is very short, and independent of the fault distance. In order to limit the rise of the current wave and reflect the incoming wave, additional reactors can be used. The steady-state fault current with a strong AC system is inversely proportional to the distance to the fault.
2. The DC converters are built from power electronic components, which are not only very expensive, but also very sensitive to overloads. This means that they need to be protected against any overcurrent.
3. Switching DC currents is not trivial, especially not when this must be done almost instantaneously. As the current does not pass through zero, the arc created when using traditional AC protection devices is not easily extinguished. Special techniques with traditional devices or newly developed devices such as circuit breakers using power electronics of extreme high power ratings and low losses, or devices that use innovative techniques such as super-conductive quenching, must be developed.
4. In a meshed system it is important to disconnect the correct (faulted) line, but keep the remaining system operational. As distance protection, as commonly used for AC power system protection, cannot be used, other means to select the correct line are needed; taking into account the very limited time that is available to make the correct decision.

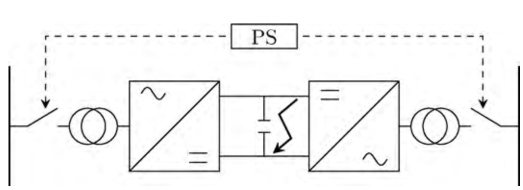

Fig. 5. Protection system (PS) in existing VSC HVDC systems.

As such, a protection system must be developed that detects the fault, identifies its location in a DC meshed system, opens the affected line in a selective manner within a few milliseconds. The AC system cannot be affected in the meanwhile.

The issue of grounding is often overlooked in academic studies, but as the DC cable usually exists between two independent insulated cables, short-circuits between the positive and negative pole are rather unlikely. A pole to ground fault closes through the grounding. A choice must be made between high and low impedance grounding, where the former will reduce the fault current (and prolongs the reaction time) while the latter will not double the pole-to-earth voltage on the non-faulted line during faults.

2.10. Communication

Depending on the control system that is going to be implemented, fast and reliable communication between different substations might be required. The size of a supergrid will extend the European continent and makes such communication not trivial. Phasor Measurement Units (PMU) or similar devices might be required when timestamps are required [16].

First of all, the reference power settings must be communicated. This can be done by relatively slow and low bandwidth communication. In case dynamic control of the terminal outputs based on remote signals is needed, for instance when the DC link would be used as a power system oscillation damper between two (or more) nodes, multiple converters need to operate in a coordinated manner in a very short time interval. This requires significant bandwidth and a high reliability of the transmission for a short time interval. In case the protection system would require communication, this would require extreme quick (ms) communication for small bandwidths. In this case, the transmission medium should be modeled as well (e.g. satellite communication is not an option because of the traveling time).

3. Control in the supergrid

3.1. Controlling flows in the DC system

The power injections in a DC grid are controlled by the converters. However, the flow in each line is not and power in the meshed system will flow according to the laws of Kirchhoff and cannot be directly controlled. However, the impedance of the lines is a simple resistance, and there is no reactive power. This means that $P_{DC} = U_{DC} \cdot I_{DC}$ and that $I_{DC} = Y_{DC} \cdot U_{DC}$, where Y_{DC} is a real matrix. The flows are determined completely by the voltages at the nodes, or rather the voltage difference between the nodes [17].

Nodes where a high amount of power is injected will have a higher DC voltage than those that withdraw power from the DC bus. In order to maintain the DC bus voltage at a correct level, the voltage must be controlled. The common approach is to use a single slack bus that controls one single DC bus voltage. All other busses will operate in active power control mode, resulting in local DC bus voltages that differ from the reference voltage according to their injection/withdrawal and the DC grid impedances. The reference node must ensure that all voltages in the entire system remain within bounds. In this slack node, the injected/withdrawn power P_{slack} is equal to:

$$P_{slack} = \left(- \sum_{i \neq slack} P_i \right) + P_{loss} \tag{1}$$

where P_i is the injected power at node i and P_{loss} is the DC loss.

As the flows themselves cannot be controlled, only the injections, congestion might occur in the DC system. In such an event, this is easily countered by a correct redispatch of the power injections in the different nodes, very similar to the situation in AC systems.

A problem might arise when a node is suddenly disconnected. This loss of a node will create an immediate imbalance on the DC grid. This imbalance will need to be removed by immediate control actions. This could potentially be done by the slack bus, if it has enough spare capacity to do so. However, this is not necessarily so, and in case the slack bus is failing, another solution is needed. One possible solution might be to develop a system which is similar to the frequency control in former UCTE, where an automatic primary control solves the imbalance, and a secondary control resets the desired setpoints.

3.2. Interaction between systems

Adding a highly dynamic system, which is fully controllable such as a VSC HVDC terminal in the system, offers both potential for improvement of the dynamic operation of the grid and potential dangers for unwanted control interactions. Special caution must be taken to develop system controls that are robust in their operation under all possible situations.

Using the controllability of the DC converter stations, it is easy to change the power injections or withdrawals on the different connections with the AC system in a scheduled manner. Similar to the electricity market where injections can be offered in blocks, the injections can be changed between terminals at predefined timings. As a result, a change in power flows throughout the AC system (dependent on which injections changed). The AC system must be able to cope with these changes: sufficient forewarning and a limited ramping speed of the power changes are needed.

3.3. Making AC islands

In [18], the possibility of reducing the AC system size to smaller segments in order to limit the propagation of faults and cascading blackouts is discussed. The coupling between grids by DC connections (as a backbone or back-to-back) would then provide the possibility to exchange power between the independent systems. In this case each system would be operated independently, with no disturbances propagating from one system to another (see Fig. 6). This scheme might have merits between different existing DC interconnected synchronous grids such as for instance in northern America, or the interconnection of the different synchronous zones in Europe. However, it would be less beneficial to separate strong interconnections such as currently exist in continental Europe.

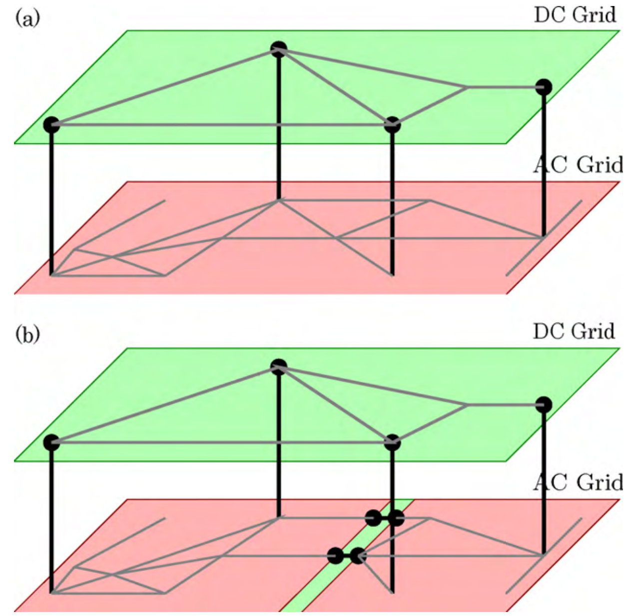

Fig. 6. DC overlay grid or DC connecting AC islands. A converter is depicted as ●. (a) DC backbone. (b) AC systems connected by DC connections.

4. Operating the supergrid

Once the supergrid is established and connected to the existing power systems, different system operators connect to the supergrid. The supergrid will allow the control of active power on all converters. All terminals will have a strong influence on the operation of both the AC and the DC systems which they interconnect. Is the supergrid, or rather each independent terminal, controlled by the system operator to which it connects or by the DC grid operator?

The controllability gives more degrees of freedom to the operation of the power system. An optimization will be needed to determine what the optimal injection is, taking into account the losses in the system, the contracted transmission capacities, line limits and the power balance in case multiple synchronous grids are connected. This seems relatively straightforward, but in a multi-zonal system, this might not be trivial, as there will be mixed objectives for every operator and for the DC grid operator. Each would like to optimize its profits and the optimal injections will often not coincide. A simple example is the problem "minimum DC grid losses or minimum system losses"? This is graphically depicted in Fig. 7 where a bulk transmission of power over a large distance can be done using the AC or the DC system.

Furthermore, this optimization needs to implement a market mechanism for the DC system which interacts with the different local markets to determine the correct injections at each node.

Such a system is likely to have negative consequences for different system operators or generator companies at different moments.

In case the supergrid would be implemented in the current European power system, this would result in an unprecedented need for coordination between the operator of the DC grid and all connected TSOs. Of course, in case a single European TSO could be set up, these problems could be minimized.

5. Techno-economic

5.1. Potential benefits of a supergrid

The benefits of adding a supergrid are fourfold:

- some remote renewable energy sources cannot be reached by traditional AC systems in an economical way;

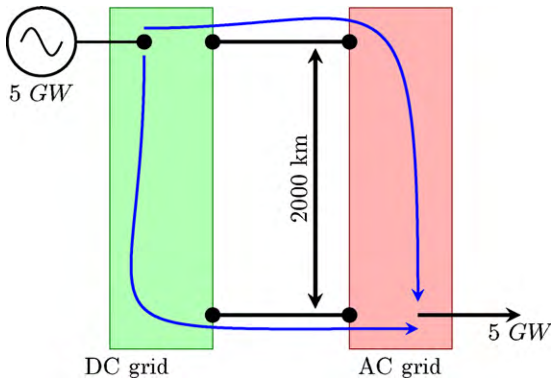

Fig. 7. Transfer of power through the AC or the DC system?

- a higher penetration and improved balancing of renewable energy sources;
- grid security and security of supply increase;
- reduction of congestion in the existing system.

It is clear that these aspects clearly provide a financial benefit for all market participants. However, it is not easy to determine what the actual financial contribution of each of these aspects is.

When large amount of power must be transferred over long distances (>50 km) and overhead lines are not possible, DC becomes the only viable solution. For example it might be impossible to tap most of the large wind power potential reserves in the North Sea and the solar potential in Africa. In case these reserves are to be integrated in the system, DC is needed. However, it is not necessary that this will be done using a "grid" as opposed to direct lines to the main AC system.

Renewable energy sources are often located far from the load centers. When looking at the energy resources in and around Europe, the North Sea and Atlantic Ocean provide significant wind power reserves.

At the same time, the North African desserts could provide large quantities of solar energy [4]. Balancing will partly be done by the non-simultaneous generation and by variable generators such as hydro power. In this regard especially the Scandinavian hydro power plants are well placed.

In a similar way, an East–West connection allows load balancing between different time zones. Within UCTE this is already so, but this effect could be enhanced by strengthening the grid.

The operational security of the system can increase by adding multiple paths in parallel to the existing system. Naturally, it requires the same operational reliability of the supergrid as the one that we currently have with the AC meshed system. On the other hand, it may be influenced in a negative way in case the grid would be subjected to a common mode failure which would de-energize the entire DC system and stop all power transfers and potentially cause generation imbalances. So although reliability and security of supply might increase, there are reservations to be made to this claim and the effective monetary value of this improvement depends on choices and developments made.

By adding transmission capacity, congestion can be reduced or more energy can be traded between regions. As investments in large-scale transmission capacity are lacking, mostly because of objections against new overhead transmission lines, congestion in the grid occurs. Because of this congestion, more expensive generation must be used, and social welfare is not optimal. Not only the additional power increases the transmission capacity, but also the controllability of the DC grid allows for additional congestion reductions and for more optimal use of the AC system.

5.2. Pay-back time

Building a supergrid will not be free of charge. Regardless of the technology used and the level of interconnection, it requires a significant investment with profits that are unsure. The question remains whether the benefits of a supergrid will outweigh the expenses and a positive return on investment can be reached in an acceptable time window. The supergrid needs to compete with other solutions which might provide only incremental improvements to the system, but at a lower cost or with a more secure or faster return.

The business model will depend strongly on the owner and the regulatory boundary conditions.

5.3. Who will own the supergrid

Investing significantly in a supergrid involves considerable financial risks. It is unlikely that a single company can invest or wants to invest in such an undertaking. More likely is that the investment is done either by a consortium of large companies or, directly or indirectly, by government(s). The companies can be generator companies, grid owners or others. In the European case, ENTSO-E (European network of transmission system operators for electricity) seems to be the most likely entity. The impact of who will invest is important on how the system is developed and how it is operated as any owner expects a return on investment.

5.4. Regulation

Ownership will also be important from a regulatory point of view. Cross-border investments in the European transmission system is subjected to EU regulation 1228/2003 [19,20]. This regulation makes a distinction between regulated (by the decision of the regulators) and merchant (where independent parties invest) investments. For the EU, merchant investments are considered as an exception to the rule. With a supergrid connecting many countries, this regulation needs revision in case a non-regulated approach is chosen. In case a regulated approach is chosen, the newly found EU Agency for the Cooperation of Energy Regulators (ACER) needs to provide a framework in which such a grid can be placed (e.g. transmission tariffs and access rules need to be clearly defined). At this moment, no common or even harmonized framework exists in which an offshore grid can be installed or operated.

6. The road to a supergrid

6.1. Small steps

As seen from the previous sections, the supergrid is not something for the immediate future. This does not mean that parts of such a supergrid cannot be built sooner. Newly built connections, or even already existing circuits can later be connected and integrated into a single system. The proposed connection between the UK and Scandinavia can form an important link in this future grid. However, most installed HVDC connections, including newly planned lines use LCC technology. The possibility of mixing LCC and VSC HVDC technology in a singly multi-terminal system is quite uncertain and might be limited to reusing some components in the system such as the cable connections.

Also, the supergrid will not be completely built in one project. Similar to the construction of the at that time 400 kV AC supergrid in the 50 s and 60 s [21], a step-by-step development is much more likely. A possible scenario is the one where first point-to-point connections to offshore AC grids (one or more wind farms) are formed, which can be later interconnected to different systems by

a new line. Later several of these smaller systems can be connected. At first only the regions with the highest economic potential are connected, with later expansions if economically viable.

6.2. One or more?

As a gradual build-up can be expected, it is not unlikely that the development of such a supergrid will start simultaneously in different locations. For instance one system might start from a North Sea offshore grid, connecting the systems of Scandinavia with continental Europe (up to Spain) and the UK, while another might start in the Mediterranean Sea, connecting the vast solar resources of North Africa to the south of Europe. Whether such independent grids should be connected to form one overlapping supergrid or rather remain independent DC grids remains an open question. In the latter case, the coupling between these systems would be through the AC power system.

6.3. Not only offshore

Although this paper has focused mainly on a DC offshore power system, this alone will not suffice. There is also a need for a strengthening onshore. Specifically the connection from the offshore grid to the most inland locations (e.g. the south of Germany or central Europe) needs reinforcements. The technology used for these reinforcements is open for discussion. ENTSO-E sees the supergrid as an answer to the ambitious goals for 2050 set by the European Union [22].

It is considered to be a (very) long-term plan, the construction of which will not start in the next 10 years.

Offshore grids, connecting several wind farms in the North Sea, as well as several additional major HVDC connections are foreseen, but no major meshed system is anticipated by 2020 by ENTSO-E [22].

7. Conclusions

The supergrid concept has received much attention in the power industry, but especially with policy-makers in Europe. This concept allows the connection of remote sources of renewable energy, possibly even up to the level that they might supply all electric energy for Europe for the foreseeable future. Furthermore, it allows balancing of energy fluctuations by making use of different energy resources that are geographically spread and connected through the supergrid. The additional transmission capacity would reduce congestion and price difference in the system and the security of supply can increase.

Technically VSC HVDC is the most probable technology to be used, especially if many underground or undersea cables must be used. However, at this moment it is not yet possible to build installation of sufficient capacity to build a supergrid, especially the cable systems are limited. Using VSC HVDC for a multi-terminal connector is also not implemented yet. Especially the protection in such a system needs new protection methods and devices. There is also a need for technical standards to be developed for this DC grid.

Also from a control issue there are several important open questions. Most importantly, the interaction between the existing AC system and the new supergrid needs to be investigated, also towards security.

From an operational point of view, the main issue is who will operate the grid, and how this will be done in the current multi-zonal environment with many stakeholders.

When considering the economics of the supergrid, there are four main advantages: it connects the different remote energy sources to the existing grid while offering additional control, it offers balancing through geographic spread, it allows a more diversified energy portfolio and in the meanwhile it increases the security of supply. However, it is a big investment with a significant risk. The rate of return is an open question and must be compared with alternative solutions which might not provide an overall solution but have a shorter pay-back time or offer lower risks to investors.

From the paper it is clear that many issues remain, but most of these problems can be solved in a relative short time frame (years). The supergrid is not something that will be built from scratch, but rather form itself as a connection for different independent smaller connections.

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